Optimization of a Cold Rolling Mill with a High Speed X-ray Thickness Gauge

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Key Words

Thickness Gauge, X-ray absorption, Automatic Gauge Control, non-contact, instrumentation standards

Abstract

The high speed production achieved by modern cold rolling mills requires reliable and robust thickness sensors. The Automatic Gauge Control (AGC) systems and hydraulic actuators in place today are capable of reacting to strip changes within just a few milliseconds so accurate measurements must be supplied with comparable speed. In order to aide process control engineers as they optimize the throughput of a given mill, the International Electrical Commission (IEC) has produced Standard 1336 defining specific terms associated with thickness measurement equipment and the testing protocol associated with verifying gauge performance. This paper describes a new sensor produced by Thermo Fisher Scientific that provides high speed measurements that allow faster feedback loops, and tighter control of flat sheet thickness. For direct feedback, various communication protocols are available such as analog signals, Profibus, or Ethernet. In addition to using the measurement values for direct feedback, single 1ms measurement values can be archived using iba analyzer allowing efficient post-rolling analysis for mill optimization and product improvement resulting in further cost savings.

Introduction

Sheet steel is an essential material for our modern lives, from the buildings we live in, the cars we drive, to the containers that hold and transport our food. With its strength and flexibility, it is the ideal material for so industrial and consumer applications. It can be recycled over and over again, reducing landfill waste and saving energy. With the ever-growing concern for efficiency and sustainability, steel producers strive to provide the world class quality strip on the first coil of a campaign, maximizing mill yield and minimizing scrap material. Steel sheet producers and their customers have agreed upon standards to describe various physical parameters for the material traded. Thickness, width, hardness, and strength are among the key variables defined in a simple product code. Both parties fully understand the standards and any disputes are governed by the scope of actual standard definition produced by ASTM or one of other widely accepted industry standard associations.

Thickness gauge manufactures are also expected to produce and test their equipment in accordance with an international standard known as IEC 61336. Unfortunately, these standards are not as well known by thickness gauge users. This can result in confusion during the gauge selection process, and unmet expectations for new mills and mill upgrade projects. This paper will review the role of the thickness gauge in a mill, present an overview of the standards to which all gauging systems should be held and present how a modern high speed X-ray thickness gauge can be used as a tool to optimize an cold rolling mill.

Cold Rolling Mills

The evolution of rolling mills has accelerated as the speed of processors and digital controls have grown by orders of magnitude. The capital cost in a rolling mill is substantial and investors understand that in order to achieve the maximum ROI and shortest payback time, the mill needs to produce high quality sheet at the fastest possible mill speeds. Diligent plant managers are always focused on safely maximizing mill output. To accomplish this, mills are operated 24 hours a day, 7 days a week. When a mill is down for any reason, the accountants not only consider the energy and labor consumed while the mill is idle, but the value of the product that could have been made during that "lost time." It is no surprise to hear that mills operate at the highest speeds allowed by their motors and drives. However, raw production in tons means nothing if the material produced does not meet quality standards.

Many believe that strip quality begins in the meltshop, and that is not far from the truth. Controlling the chemistry and thermal history of the steel not only assures the grade produced will meet the mechanical properties desired of the final product, but that the strip will handle the tons of pressure and tensions of the high speed rolling process. Table I summarizes the typical thicknesses and rolling speeds for each mill type. Not surprisingly, as the material gets thinner, the speeds increase dramatically.

Table I: Overview of Steel Rolling Mill parameters

	Hot Roughing Mill	Hot Finish Mill	Cold Rolling Mill
Maximum Thickness	> 400 mm	20-50 mm	3-20 mm
Minimum Thickness	20-50 mm	3-20 mm	0.100 mm
Rolling speeds (meters per min)	~ 100	~ 1000	~ 2000

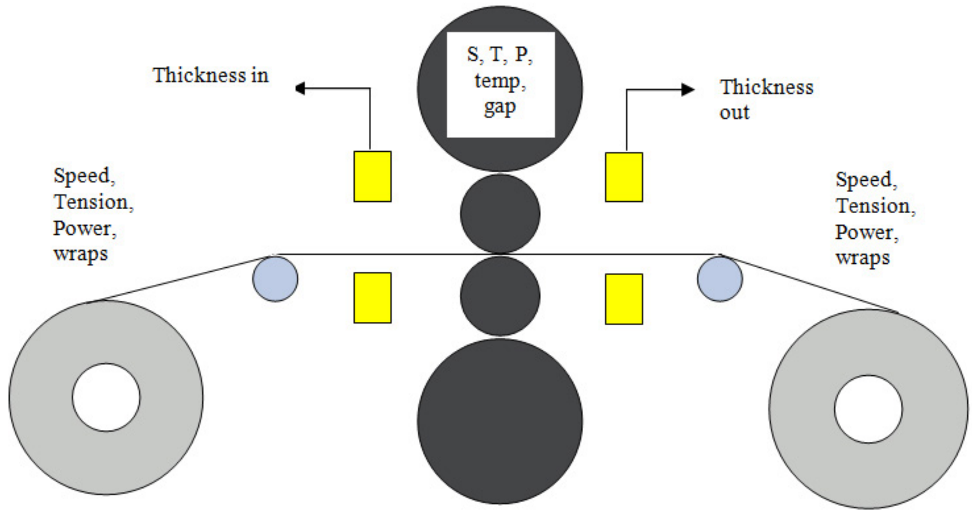
Automatic Gauge Control

The average human response time is on the order of a quarter of a second, at the maximum rolling speed of a cold or foil mill, 8 meters of strip is produced. It is easy to see why Automatic Gauge Control (AGC) is an essential component of modern rolling mills. Comprehensive AGC algorithms incorporate readings from dozens of sensors around the mill.

Some of the key AGC input parameters are speed and tension. (See Figure 1) Conservation of mass dictates that the mass per unit time entering the mill must equal the mass per unit time exiting the mill. So as the material is rolled thinner, the speeds must increase. If the drive motors are off, even by a few centimeters per minute, the strip may break or cobble with catastrophic results. There is a delicate balance between the reduction caused by the mill force, and the reduction caused by drawing (extruding) the material through the gap.

For measurement of thin metallic coatings applied to steel strips this X-Ray Fluorescence (XRF) principle is used: The coated steel strip is exposed to a primary beam of photon radiation. This photon radiation can be gamma rays or X-rays, having sufficiently high energy to stimulate excitation and emission (fluorescence) of X-rays. The excitation of iron atoms in a steel strip leads to emission of fluorescence radiation with an energy of 6.4 keV (1 kilo electronvolt = 1.6 . 10-16 J).

Figure 1: Selected AGC input variables for a simple single stand mill



When a mill is operating at 1800mpm, the material moves 3 cm every millisecond. If the mill is using 0.5 meter diameter rolls, the circumference of the roll would be roughly equivalent to 50 milliseconds. In order to see any eccentricity or periodic event related to a roll of this diameter, one would need to have a thickness sensor not only capable of operating at 5ms, but being able to provide measurements with manageable signal to noise values.

Thickness Gauge Selection

While there are several choices in thickness gauge technology, there really is only one choice for the speed and accuracy requirements demanded in optimizing a cold rolling mill; the X-ray gauge.

Direct contact gauges have the advantage of being insensitive to alloy, the measurement stylus marks the strip, and the mechanical tolerances of the frame prevent measurement near the centerline of the strip. Additionally, the small measurement spot size of the stylus translates microvariations in the strip surface into a noisy signal. While these variations may actually be in the strip, the signal needs to be filtered to reduce the noise, and the filtering will delay responses to actual longer term changes. Therefore, high speed AGC is not practical with contact gauges.

Optical laser gauges that employ triangulation for distance measurements are available, but they have significant drawbacks in the cold mill. First, they have a relatively narrow gap between the top and bottom frame arms which can turn this non-contact gauge into a contact gauge during strip tail out. Additionally, like the contact gauge, the sensor frame is designed with a short arm length to limit the effect of thermal expansion on the measurement. This in turn limits the allowable strip width, or restricts the measurement area to a few centimeters from the edge. Laser gauges can also be sensitive to the high amount of steam and mist that occurs in a rolling mill. Additionally the laser camera technology limits the resolution of measurement to a few microns. While this is acceptable in process line applications, it does not meet the needs of the high-speed cold rolling mills.

Non-contact radiation based thickness gauges can use either radioisotope or X-ray sources. However in the case where the gauge measurement is to be used in a closed loop control or Automatic Gauge Control (AGC) system, there is really only one solution, X-rays. The number of photons emitted from an X-ray source is approximately 1000 times that of the commercially available isotopes. Due to the statistical nature of radiation detection, measurements made with more photons per unit time have a better signal to noise ratio, and consequently a more true measurement. In the case of X-ray versus isotope, the noise level for an isotope is on the order of 20 to 30 times worse than that of an X-ray based sensor when the same averaging time is used. Statistical noise at that level creates a situation where small changes in thickness are lost in the noise of the signal. While higher activity or multiple isotope pellets might be used in an effort to increase the signal, the regulatory and safety considerations make this option prohibitive. Another approach to improve the noise on isotope based systems is to increase the averaging, or response time. However, when this is done, small, and instantaneous changes in product thickness are blurred to the point of not being seen. (See Figure. 2)

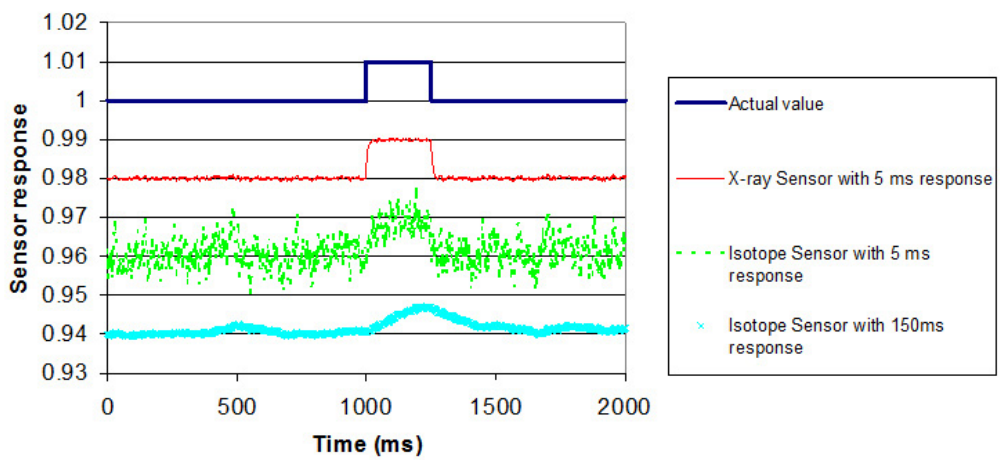


Figure 2: Simulated sensor responses to a 250 ms, 1.0% deviation from target

Just as low signal to noise ratio is a serious factor in source selection, one must take care to select a source of a proper energy as to not have too much signal. While there may be a small spares inventory savings to use a single source type across a number of rolling mills, there are serious performance drawbacks. If an X-ray gauge is operated at too high of an energy, the dynamic range of the detector output is reduced, limiting the measurement resolution and precision. In the case of thin strip production at around 250 microns, a 10 micron change in thickness results in a signal change of less than 0.2% at a photon energy of 150 keV, whereas the same thickness change at a photon energy of 40 keV will produce a signal change of over 7% (See Figure 3). When the statistical noise on the measurement is +/- 0.1%, it is easy to see that the 150 keV source is just too much for the thin strip application.

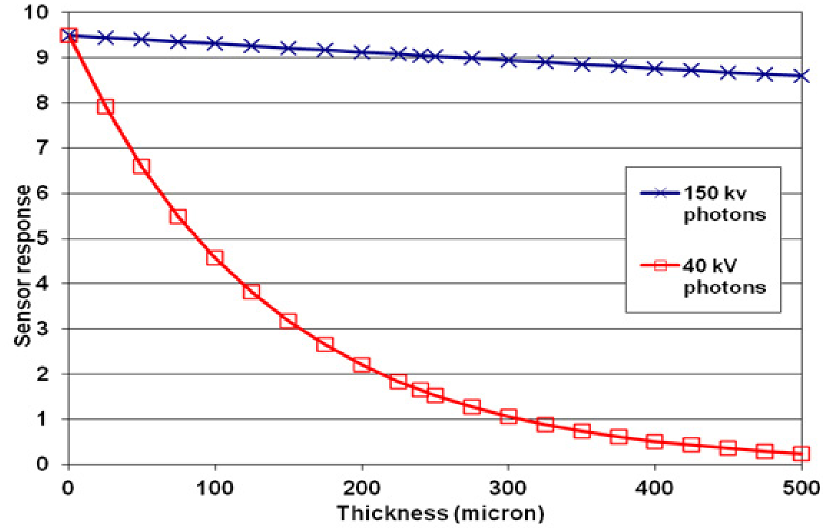


Figure 3: Sensor response as a function of steel thickness for different photon energies

International Standards

International organizations like the ASTM, Japanese Standards Association and others provide guidance on not only alloy chemistry tolerances, but sheet dimensional tolerances and mechanical properties as well. For Instrument Suppliers, the International Electrotechnical Commission (IEC) has produced standards to provide guidance and definition for specific terms and tests used. The standards act as a consistent scale to compare one instrument to another without confusing nomenclature obscuring the true performance of each.

The Nuclear Instrumentation Technical Committee (IEC Technical Committee 45) produced IEC 61336 "Thickness measurement systems utilizing ionizing radiation – Definitions and test methods." The first committee release was in 1983, and an update was drafted in 1996. The document is available for purchase from the IEC at http://webstore.iec.ch/webstore/webstore.nsf/ArtNum_PK/21703?OpenDocument , as such we cannot reproduce it here. The Standard first defines common terms in order to clarify what specific words mean. For example the "mean response time" may be called the "first time constant" by some, and something else by others. (See Figure 4) The fixed definitions avoid any ambiguity in interpretation. They additionally provide guidance in setting up and carrying out the tests defined in the second part of the standard.

The standard dedicates no less than nine terms to clarify time based parameters. Some are related to defining the time associated with the time taken to respond to a change, while others are related to the digital processing of signals. This is particularly critical with the advent of high speed data processors. Incoming data can be manipulated and processed by advanced filters to mask or hide true statistical variations. As depicted in Figure 2 above, radiation measurements are statistical by their very nature. All noise figures should be quoted with a reference to the number of Sigmas, or confidence levels (CL). Most gauge manufactures present 2 sigma (95% CL) noise figures, but not all. Straightforward data processing provides for predictable results and a better representation of the process dynamics. If a change occurs in the process, advanced filtering may portray a portion of the change, but not the full change. Process engineers and their AGC algorithms may over react, or under correct thanks to the manipulated data.

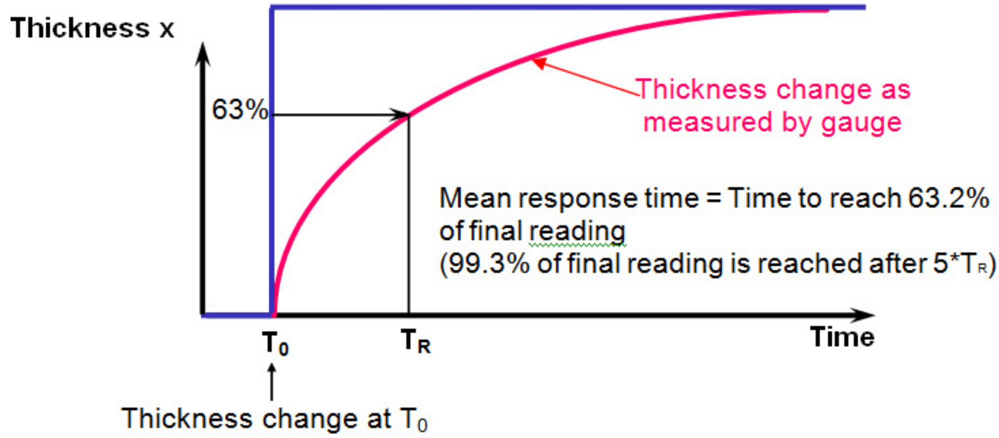


Figure 4: Graphical representation of gauge response to an instantaneous thickness change

In order to ethically improve the speed of the sensor response to change, without increasing the statistical noise on the measurement, the physical characteristics of the sensor need to be optimized for the application. The raw signal; must be shielded to remove as much electrical noise as possible. In an ideal instrument, the radiation detector output is digitized right away. The analog detector signal is converted to a digital number within a few millimeters of its origin. This practically eliminates the possibility of electrical noise impinging on the signal. In comparison tests, following the IEC 61336 guide, the noise on the new designed detector improved by a factor of 30%. Additionally, users of this type of system can benefit further by taking advantage of the detector's ability to operate at a 1ms mean response time. At this speed, and with the reduced noise, process engineers have the tools to analyze data at high speeds, revealing mill chatter and other higher frequency anomalies.

In a typical rolling mill that produces sheet steel at 250 um, the noise at a 10 ms mean response time might be on the order of +/-0.10% (2 sigma). With the improved signal processing of this system the noise will drop to +/-0.07% (2-sigma). For a mill that produces 2,000,000 tons a year, that translates to a savings of almost $360,000 in raw material alone (using HRC price at $600USD per ton).

An additional benefit to digitizing the signal so early in its journey to the AGC system is speed. Once digitized, the data can be processed with out the time consuming ADC / DAC conversions. The reduction of a few milliseconds of process delay time can assure the AGC has time to fully correct any strip thickness deviations. This can result in higher quality product.

Data Archiving

A final benefit is realized in the powerful tool of data archiving. This ideal system is available with a software feature that stores any gauge data stream in the iba ".dat" format. This format is gaining popularity as the iba PDA data analysis tool also grows in popularity. The flexibility of the iba visualization tool is its real strength. A simple example of the flexibility is depicted in Figure 5 showing a coil report with the thickness data presented as a function of length, with tolerances and coil statistics. Easy to use features allow for time based, and length based data analysis. Built in mathematical tools such FFT can point process engineers to mill components that might need maintenance. In this situation, mill downtime can be best managed, and unplanned downtime dramatically reduced.

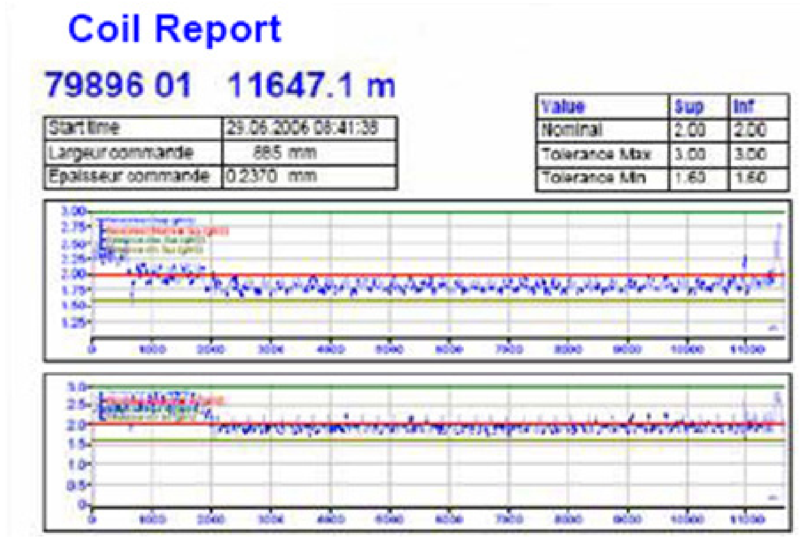


Figure 5: Typical coil report using iba data archiving tools

The data archiving feature can also be configured to accept and record data from other sensors with in the mill. Any data point that is available to the mill computer through an Ethernet connection can be collected by the system to allow for comprehensive data analysis. Thus permitting the pairing of thickness measurement output to mill tensions and speeds in such a way that complies with the IEC 61336 testing standards. The IEC 61336 Annex B defines appropriate test points for data collection and analysis. While traditional analog outputs are typically used for gauge validation, it is equally acceptable to use the data transferred via Ethernet, or other means to a data archive.

Summary

Advances in online control of flat sheet have necessitated a state of the art X-ray based sensor system to provide high speed/low noise measurements permitting producers to realize material savings and quality improvements. The ideal sensor would be housed in a robust frame designed for the rigors of the rolling mill environment. The complete package must be manufactured and tested following IEC 61336 definitions which assure process engineers receive clear thickness data with out ambiguity. Thus allowing for mill optimization to achieve world class quality and strip uniformity at the highest rolling speeds. The result would allow for the maximum return for rolling mill owners and investors.

Acknowledgement

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